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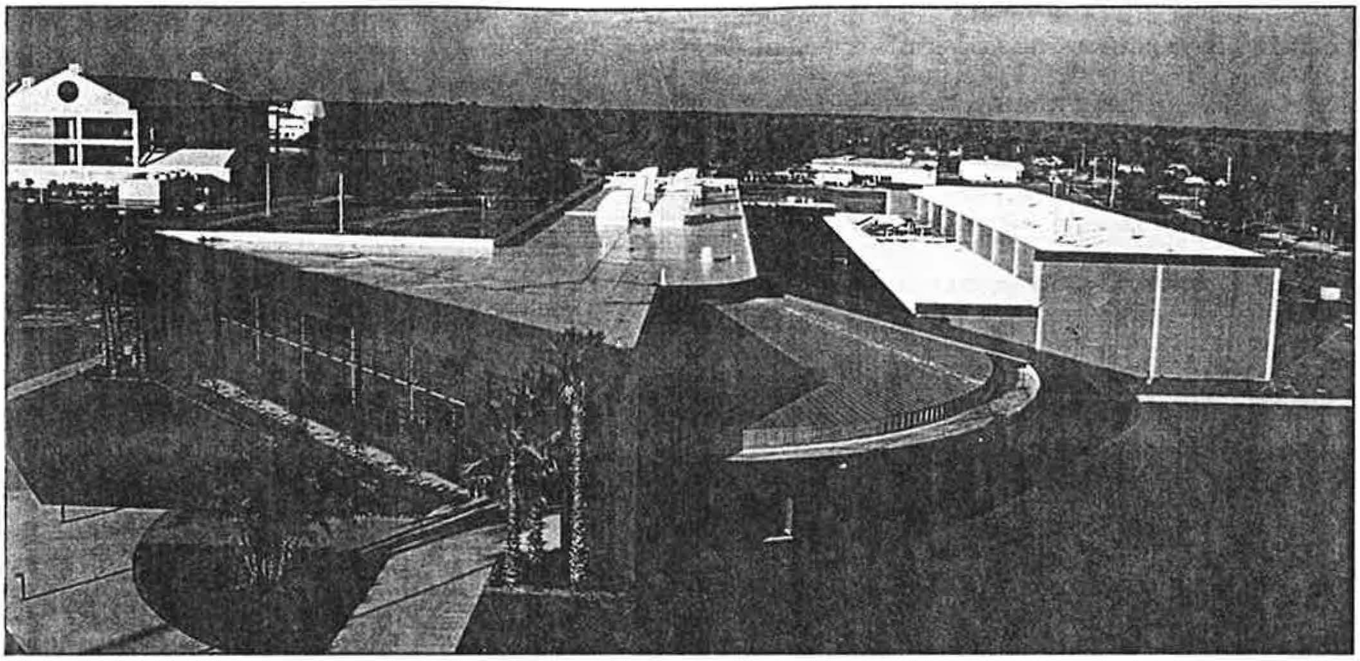

Figure 1: The Florida Solar Energy Center has three buildings: an office building, a visitor's center, and a laboratory complex.

Energy-Efficient Office Building Design For Florida's Hot and Humid Climate

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and

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Florida's hot and humid climate poses unique challenges to architects and engineers seeking energy-efficient office building designs. The impact of internal loads on cooling, the intense solar conditions and the need for increased ventilation set against high relative humidity, all limit the effectiveness of many conventional methods of reducing energy use. To provide a high-visibility demonstration of design solutions, the Florida Solar Energy Center (FSEC) has built a state-of-the-art office complex for its new facility in Cocoa, Fla.

Design Objectives

While recognizing that the judgment and experience of the architect and engineer still remain the most important elements of successful building design, we desired a more analytical assessment. Our objective was simple *within the limits of our climate, to design and construct the most energy-efficient office building possible.*

Obviously, cooling needs dominate energy use in Florida. As elsewhere, cooling equipment efficiency plays a large role in commercial building energy conservation. However, more subtle opportunities lie in addressing the cooling load itself.

Minimizing the cooling needs in commercial buildings often centers on reducing internal lighting and equipment energy use. In Florida's climate, external envelope and ventilation loads can be significant as well. When providing energy design assistance, our staff typically advises a high-efficiency lighting system, reflective roof finishes, east-west orientation, and high-performance glazing. These recommendations are based on the relative magnitude of each

About the Authors

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component. For instance, elimination parametric analysis [1], with an hourly simulation of a conventional single-story office building prototype in Orlando shows that about 30% of the annual cooling load is attributable to heat produced by lighting, 20% to solar heat gain through windows, 15% to roof heat gain and 13% to heat from internal equipment.

The lighting system is not only the largest component of the cooling load, but also second only to HVAC in electrical consumption. Thus, lighting improvements yield large, compound rewards. Perhaps the most challenging lighting measure is *daylighting* which takes advantage of Florida's abundant solar resource. Although this strategy has great potential [2], it can not be pursued haphazardly. To be acceptable, the daylight provided to work spaces must be of high quality. This means diffuse, cool sunlight; direct beam radiation can thwart a daylighting design. With uncontrolled glare and localized overheating, occupants will resort to blinds or curtains for relief [3].

With these objectives in mind, the schematic building design was analyzed in detail using a hourly computer simulation to predict annual energy consumption. Then, a variety of energy conservation measures (ECMs) were simulated to find a combination of options that would reduce energy use to minimum levels.

The Building

The completed new FSEC facility is pictured in *Figure 1*. In accordance with established practice, the long axis of the complex is aligned east-west to minimize solar heat gains through glazing and maximize daylighting potential. The facility is composed of three major building elements: an office building, a visitor's center, and a laboratory complex.

The office building is a long and narrow 41,000 ft^2 (3,809 m^2) two-story structure that includes offices, visitor's center and meeting rooms. The laboratories, because they are dominated by process loads, were not considered in our energy analysis.

A four-inch (1.9 cm) concrete slab forms the floor for the building. The exterior wall assembly consists of steel studs sheathed by an inch (2.5 cm) of foil-faced isocyanurate insulation (R-7; RSI 1.2) to reduce thermal bridging. This is covered with a prefabricated metal skin on the exterior. Between the studs R-11 ft^2 h °F/Btu (RSI-1.94m^2 K/W) fiberglass insulation is located. The roof assembly consists of an EPDM single-ply membrane over 4 inches (10.2 cm) of rigid insulation (R-20 ft^2 h °F/Btu) on a metal deck over an unconditioned plenum. The base case solar absorptance of the roof and walls is assumed to be 0.80 and 0.70, respectively.

Conventional commercial building characteristics for Florida were assumed for the base use building:

- A standard reciprocating chiller (0.96 kW/ton; COP=3.66) and a VAVS system with hot water reheat coils. Water is heated by condenser heat reclaim supplemented by natural gas.
- Single pane aluminum frame windows without a thermal break (shading coefficient with blinds = 0.6).
- A lighting system consisting of recessed fluorescent fixtures with four T-12 F40 cool-white lamps in a standard troffer with magnetic core-coil ballasts; 40 W incandescent lamp exit signs.[1]
- No overhangs or other exterior shading devices. Many modern commercial buildings in Florida feature little fenestration of exterior glazing.

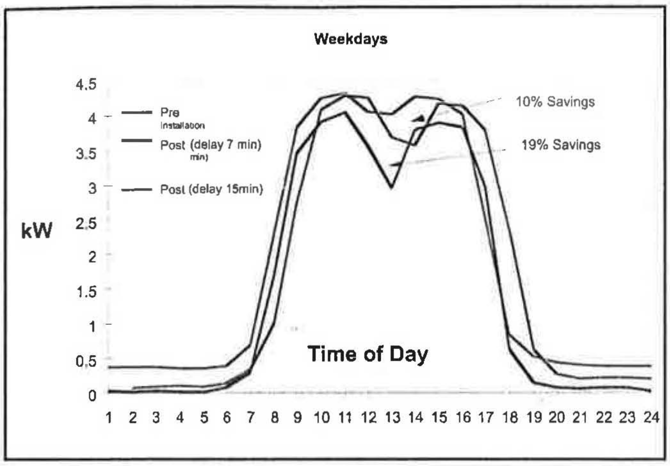

Figure 2: Lighting use profile for office building with and without occupancy sensors for time delays.

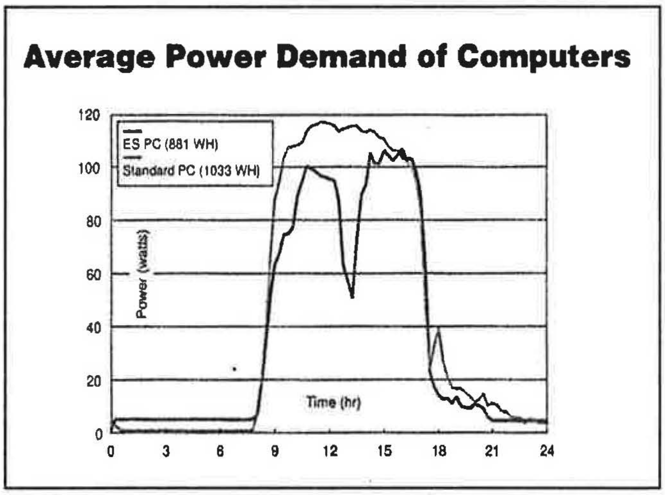

Figure 3: Comparison of low-energy Energy Star personal computer system with standard model.

- Standard office and computer equipment with conventional lighting controls.
- Fixed speed fans and pumps.

Simulation Model

We used the DOE-2.1E computer simulation program for our analysis of the facility [4]. DOE-2 predicts the hourly and annual energy use and costs of a building given weather data, a detailed description of the building including systems and usage patterns, and the prevailing utility rate structure. The program is particularly suited to the analysis of complex commercial structures since it incorporates detailed models of the building heating and cooling systems. It also predicts the ability of daylighting to offset electrical lighting needs. The simulations were performed, both on an annual basis and for the peak summer and winter days. Typical Meteorological Year data (TMY) for Orlando, Florida and standard engineering methods were used for the analysis [5].

The base building connected full-load lighting power density is 2.0 W/ft^2 (0.19 W/m^2). This is typical for standard luminaries and lamp types*. In accordance with *ASHRAE Standard 62-1989*, outside ventilation air is introduced into the building at a rate of 20 cubic feet per minute (20 cfm = 9.4 L/s) per occupant. The average occupancy for the office building is 150 persons. Since the building is positive pressured, natural air infiltration is assumed to be negligible at 0.05 ACH. The occupancy schedule is zero between midnight and 7 a.m., with levels reaching 100% by 8 a.m., dipping briefly during the noon hour, dropping to 30% at 5 p.m., and then tapering off to zero after 11 p.m.

Use of Empirical Data

To accurately model and predict the performance of any building, accurate input data must be available. Norford et. al. (1994) [6] showed convincing evidence that failure to document energy use schedules and operating assumptions were powerful explanations for the shortfall in predicted versus actual performance in "low-energy" office buildings. To address this potential shortcoming, the *base case* building definition and several ECMs for our analysis were defined using empirical data gathered from experiments at our previous facilities. For instance, the thermostat settings and HVAC operation schedules were an accurate reflection of the measured conditions prevailing at FSEC's Cape Canaveral site.

Similarly, our weekday lighting schedule, as well as the occupancy sensor ECM, were based on the measured lighting energy use in one of our main office buildings over a six month period. An occupancy sensor retrofit study provided a detailed portrait of lighting use patterns at our previous facilities and the technology's savings for our specific application. This is of particular importance because occupancy sensors do not readily lend themselves to savings estimates since results depend on behavioral characteristics [7]. Measured savings were only about 15% whereas most estimates for office buildings are twice as large. As shown in *Figure 2*, the majority of the lighting energy reduction is realized at noon and after normal working hours.

In some cases, monitored input data were not available. In these cases, we used the most reliable information available. For example, based on metered end-use data for 19 office buildings, daily equipment loads from computers, copiers and other office equipment were estimated to peak at 0.77 W/ft^2 (0.07 W/m^2) [8]. An office equipment schedule was created with the minimum consumption reaching approximately 45% of the daytime peak value.

Predictably, the largest equipment load in a research institute's facilities is from personal computers (there are approximately 160 PCs in use. Thus, we looked to Environmental Protection Agency's new *Energy Star* computer program to address this load. The *Energy Star* program has made available low-energy personal computer systems that often cost no more than comparable machines without the energy savings features. From 1994-1996, FSEC metered the power use for both standard and a new *Energy Star* systems over a long period. The overall energy savings were 26% as shown in *Figure 3* [10]. Although the test results were conservative, we used the resulting 24-hour demand profile to alter the equipment load shape input into DOE-2.

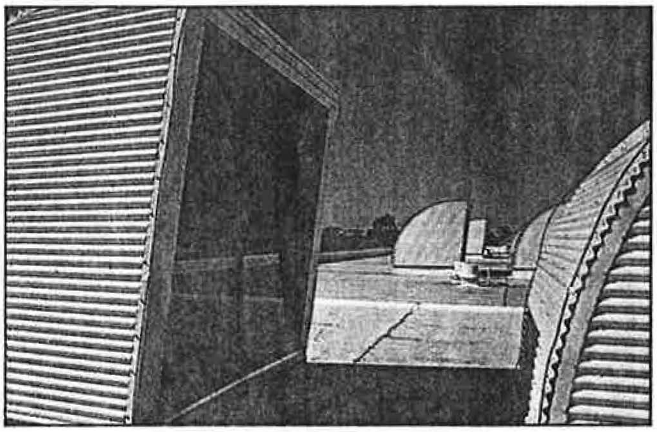
Figure 4: The roof is covered with white single-ply membrane to reduce heat gain. The north-facing light monitors project daylight into the building center.

Perhaps most importantly, we performed tests to determine the feasibility of our largest potential savings measure -- daylighting. There were a number of uncertainties highlighted by previous studies that made performance verification an imperative [11,12]. How accurate was the DOE-2 daylighting model? Might the presence of blinds effect the results and how well would manufacturer's equipment perform against specifications? Using two side-by-side offices at FSEC, the daylighting dimming systems demonstrated an average electrical lighting reduction of nearly 30% during daytime hours [12]. Our findings agreed well with the daylighting performance prediction from DOE-2. The findings are given in an accompanying article.

Controlling Humidity

Maintaining proper humidity levels within air-conditioned buildings in Florida is an omnipresent concern. With increased requirements for outside air for ventilation, the latent loads on the space conditioning systems in Florida often exceed the sensible loads. Thus, it becomes imperative to carefully engineer the HVAC system to provide effective control of interior moisture loads under part-load conditions.

Our first steps were conventional. These involved minimizing internal moisture generation and reducing vapor diffusion through the building envelope by using exterior materials and finishes with high vapor resistance. Producing positive pressure with properly dehumidified ventilation air minimizes air infiltration into the building as well as vapor diffusion through wall and roof cavities.

However, as a building is made more efficient, and sensible cooling loads are reduced, the latent load quickly becomes the dominate factor in the cooling system's ability to maintain comfort. Suitable sizing of cooling equipment becomes important in providing dehumidification under part-load conditions. Thus, as sensible cooling loads in a humid climate are reduced, the space conditioning system must be continually re-sized in response. Over-sized cooling systems exacerbate the problem since the latent capacity of chilled water coils falls off more quickly than does the sensible capacity. Other common energy saving practices, such as supply air or chilled water reset with outside air temperature,

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**At the time our initial analysis was conducted in 1991, this was considered a typical office lighting system. Since that time improved lamps and electronic ballast have become more common. However, we retained this configuration as the base case for our analysis, in part to illustrate the desireability of the new lighting systems that typically comply with ASHRAE Standard 90.1.*

Measure Description	Use kWh	Peak kW	Gas MCF	A/C Size Ton	kBtu/ft yr	Elec Cost $/Yr	Gas $/yr	Total $/yr	Savings $
Base Case FSEC	850,532	320	320	140.8	71.3	$72,930	181	$73,111	0
T-8s w/elect ballasts	640,993	256	681	125.7	54.6	$55,843	293	$56,123	$16,988
Spectrally selective glazing	550,354	212	275	97.9	46.2	$47,026	118	$47,145	$ 8,978
Daylight dimming ballasts	449,435	169	337	85.5	38.0	$37,673	145	$37,818	$ 9,327
Helical-rotary chillers	397,833	142	279	85.5	33.6	$32,667	120	$32,787	$ 5,031
Energy Star equipment	366,091	147	307	84.2	31.0	$30,859	132	$30,992	$ 1,795
Reflective roof finish	353,732	129	240	75.0	29.8	$29,253	104	$29,356	$ 1,636
Occupancy sensors	344,245	131	257	74.5	29.1	$28,823	111	$28,934	$ 422
Variable speed fans	336,753	131	266	74.5	28.5	$28,498	115	$28,613	$ 321
Energy Mngt. System	331,548	129	197	70.9	27.9	$27,543	85	$27,628	$ 985
Variable Speed Pumps	326,693	129	189	70.9	27.5	$27,233	81	$27,315	$ 313
Controlled Ventilation	323,800	125	186	68.2	27.2	$26,899	80	$26,979	$ 336

Table 1: Incremental Analysis of Energy Efficiency Measures for FSEC Building

will further reduce coil latent capacity under part-load conditions.

In humid climates, ventilation air must be continually dehumidified to yield acceptable moisture control. In the past this has been accomplished by over-cooling the mixture of ventilation and return air, and then using terminal reheat coils to bring the air temperature levels back to comfort conditions. Even when electric reheat is avoided, however, this approach is energy intensive, and minimizing its annual use was a priority design objective.

A useful concept in the design of ventilation systems for commercial buildings in humid climates is the "central fresh air unit." This uses a dedicated air conditioner or cooling coil to cool and dehumidify the outside ventilation air prior to being mixed with return air within the space conditioning system. By directly conditioning the moist outside air before being mixed with system return air, the thermodynamic effectiveness of moisture removal is improved. For a given chilled water coil, not only is moisture removal increased by such a dedicated unit, but the coil's cooling capacity is also enhanced.

A fresh air unit also provides a centralized opportunity for filtration or the use of devices to exchange sensible and latent heat between the supply and exhaust air streams. The air can be pre-cooled and dehumidified using either heat pipes, chilled water coils, a dedicated low SHR vapor-compression air conditioner or a rotary enthalpy heat exchanger.

Simulation Results

Eighteen ECMs were considered in the energy analysis. A number of studied measures, often advocated in more temperate zones, were found to be of little value in Central Florida's humid climate. For instance, an economizer cycle showed little savings, particularly when realistic enthalpy limitations were established. Similarly, higher than code-mandated levels of wall and roof insulation produced little benefit. Ultimately, ten measures were found to confer beneficial energy savings.

Primary Measures

- Lighting: Incorporation of a high-efficiency lighting system (0.9 W/ft^2; 0.08 W/m^2) consisting of T-8 fluorescent lamps in a reflective troffer with electronic ballasts reducing lighting electrical consumption.
- Glazing System: Specification of high-performance windows consisting of spectrally selective glazing units with a high visible transmittance (0.56) for daylighting and a very low shading coefficient (0.33) for rejecting unwanted solar heat gain [13]. A low unit U-value (0.31 Btu/hr ft^2 °F) (1.76 W/m^2 K) provides control of conductive gains under peak load conditions.
- Daylighting: A long and narrow perimeter office plan with extensive north and south facing glazing provides high quality daylighting suitable for perimeter office illumination. This, coupled with solar control devices on the south facade enables effective use of daylight. Dimming electronic ballasts are controlled by photometric sensors which adjust ballast output in response to available daylight to maintain a constant desk-top illumination level. Roof-top monitors project daylight into the core zones.
- HVAC: Substitution of two high-efficiency (IPLV=0.65 kW/ton; COP=5.41) helical-rotary screw chillers for a standard reciprocating chiller. These are used in tandem to take advantage of their attractive part-load characteristics (0.60 kW/ton at 50% load condition) while increasing overall cooling system reliability. Parallel fan powered VAV boxes are used to exchange air between the building core and the perimeter

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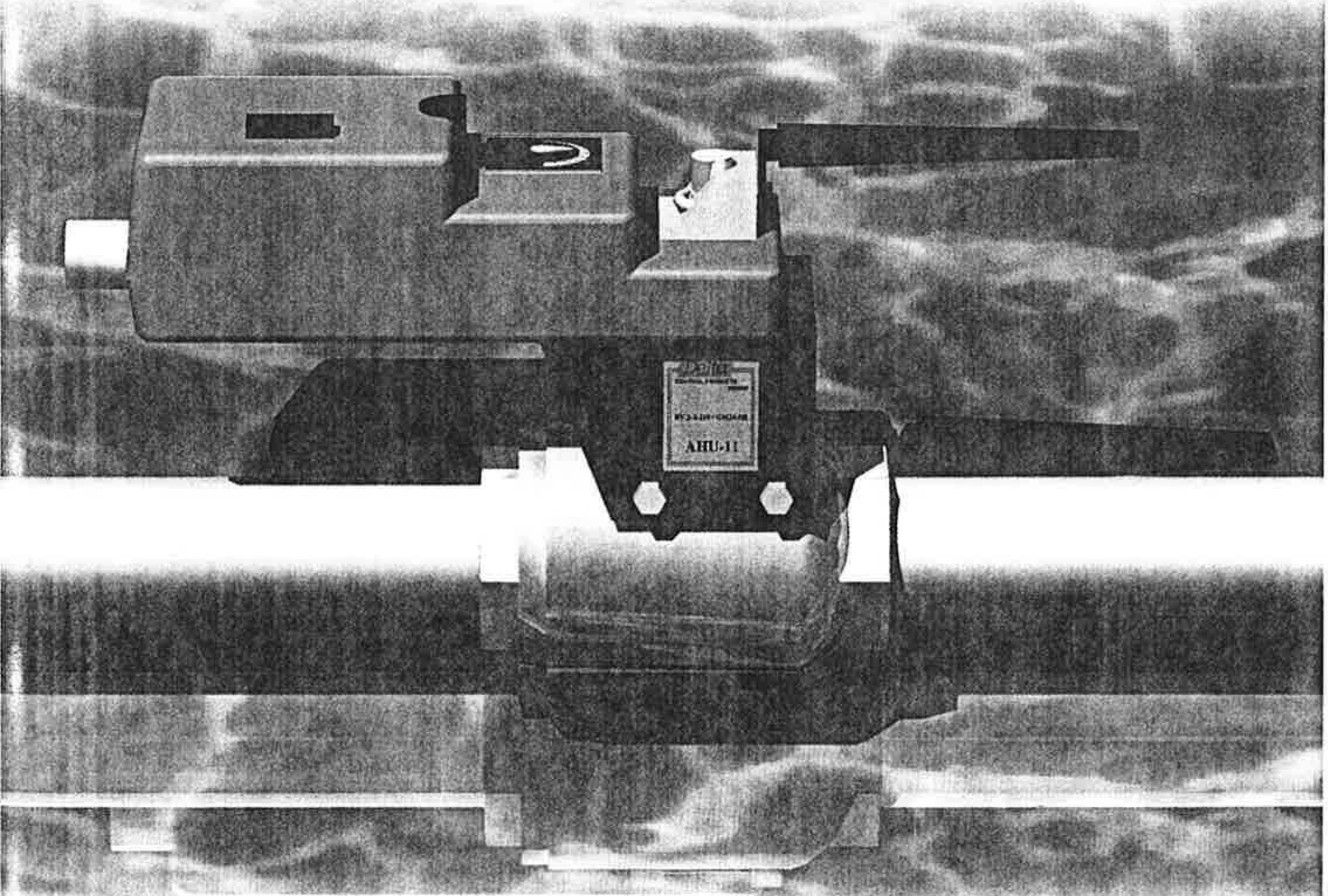

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zones, significantly reducing the need for re-heat. Straight cool VAV boxes are used for the building's core zones. High-maintanence, high energy-use fan powered induction boxes were avoided. Variable speed fans are used to reduce fan-energy.

- Humidity Control: The new facility uses a central fresh air unit with heat pipe heat exchangers. The low temperature side of a closed-loop refrigerant heat pipe is first used to lower the temperature and moisture of filtered outside air. The air is then passed through a chilled water coil for further cooling and dehumidification after which the condensing side of the heat pipe adds heat back to the air stream. Should the air still be too cool to be introduced to the space, natural gas fired hot water coils are used to add reheat.

Secondary Measures

- Energy Star Equipment: A purchase policy to acquire energy saving "Energy Star" personal computers, printers and copiers to replace existing equipment. Direct savings of 100 - 200 kWh per year per workstation.
- Reflective Roof Finish: Selection of a reflective white EPDM single-ply roofing membrane rather than gray or black to reduce heat gains to the top floor plenum (*Figure 4*). Experiments by FSEC whitening the roofs of nine residences over a three-year period have shown an average 19% reduction in air conditioning energy use [14]. Although savings are certain to be less in internal load dominated commercial structures, increased aesthetic acceptance and low incremental cost should make this a beneficial measure for non-residential buildings in Florida.
- Variable speed fans and pumps: Inverter controlled drives for larger chilled water pumps and variable speed fans rather than inlet vanes for the VAV system allows improved part load performance with demonstrated energy savings [15]. Analysis showed it to be cost-effective to use variable frequency drives for motors larger than 15 hp (11.2 kW).
- Demand Controlled ventilation: The overall building outside air ventilation rate is decreased from an average of 20 cfm/person to 15 cfm/person (9.4 - 7.1 L/s/person) using CO_2 sensor-controlled ventilation for intermittently occupied spaces and zones.

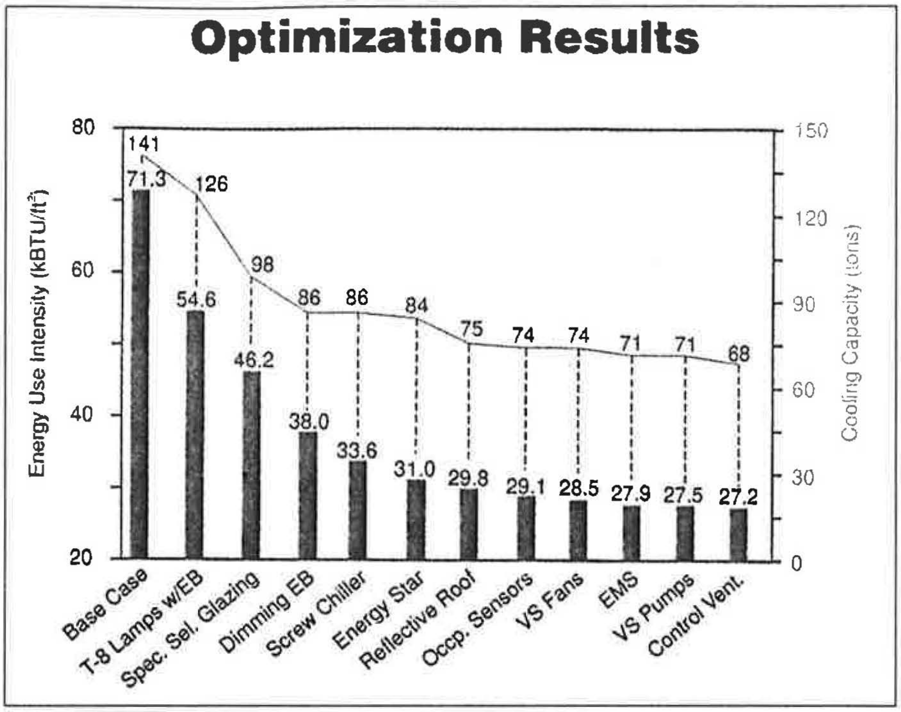

Figure 5: Graphic illustration of the building optimization process. Shown are incremental reductions in energy use (kBtu/ft²) and cooling system capacity (tons) from each measure. The optimized building reduces the base building energy use by 62% and cooling capacity by 52%.

- Energy Management System (EMS): Our simulation assumed that the finer control tolerance of the Direct Digital Control (DDC) systems coupled with the EMS permits an increase in the cooling setpoint from 75°F to 76°F (23.9 - 24.4°C) as well provide optimal stop capability. This results in a very conservative estimate of annual EMS savings (5%) [16]. The temperature maintained inside our previous facilities averages 75.6°F (24.2°C) based on measurement.

Optimization Analysis

After the analysis of the individual ECMs, we added the successful options to the base case in an incremental fashion to determine a package of measures that would yield optimum performance. Although economics are ultimately important with any design, we desired to examine the energy-reduction potential from a technical standpoint. *What combination of measures would provide the greatest energy reduction?*

With this methodology, all potential ECMs were examined. The one which yielded the greatest energy savings, T-8 lamps with electronic ballasts, was incorporated into the building model resulting in a new *base case* building. Then, all remaining measures were re-evaluated for the revised *base case*. This process, optimization by steepest descent, continued until there were no additional measures with significant benefits as shown in *Table 1* and *Figure 5*.

The optimized building design was predicted to reduce energy use and associated operating costs by more than 62% over the schematic design. Lighting-related measures accounted for 58% of the identified savings in the package.

Many of the more successful strategies, particularly the improved lighting system and the spectrally selective glazing, had a beneficial impact on the predicted peak electrical loads. Reduction to peak demand is not only desirable for utilities, but also to building owners since monthly demand charges comprise a large fraction of energy costs. The optimum package of measures was projected to reduce the building peak demand to 38% of its original value.

Benefits also accrue from the reduced size of the HVAC system. The required cooling capacity for the office building drops from 141 tons (496 kW_t) for the base case to only 68 tons (239 kW_t) for the optimized building. This saves an estimated $40,000 in avoided expenses for the larger chiller and cooling tower. Including these credits, the incremental

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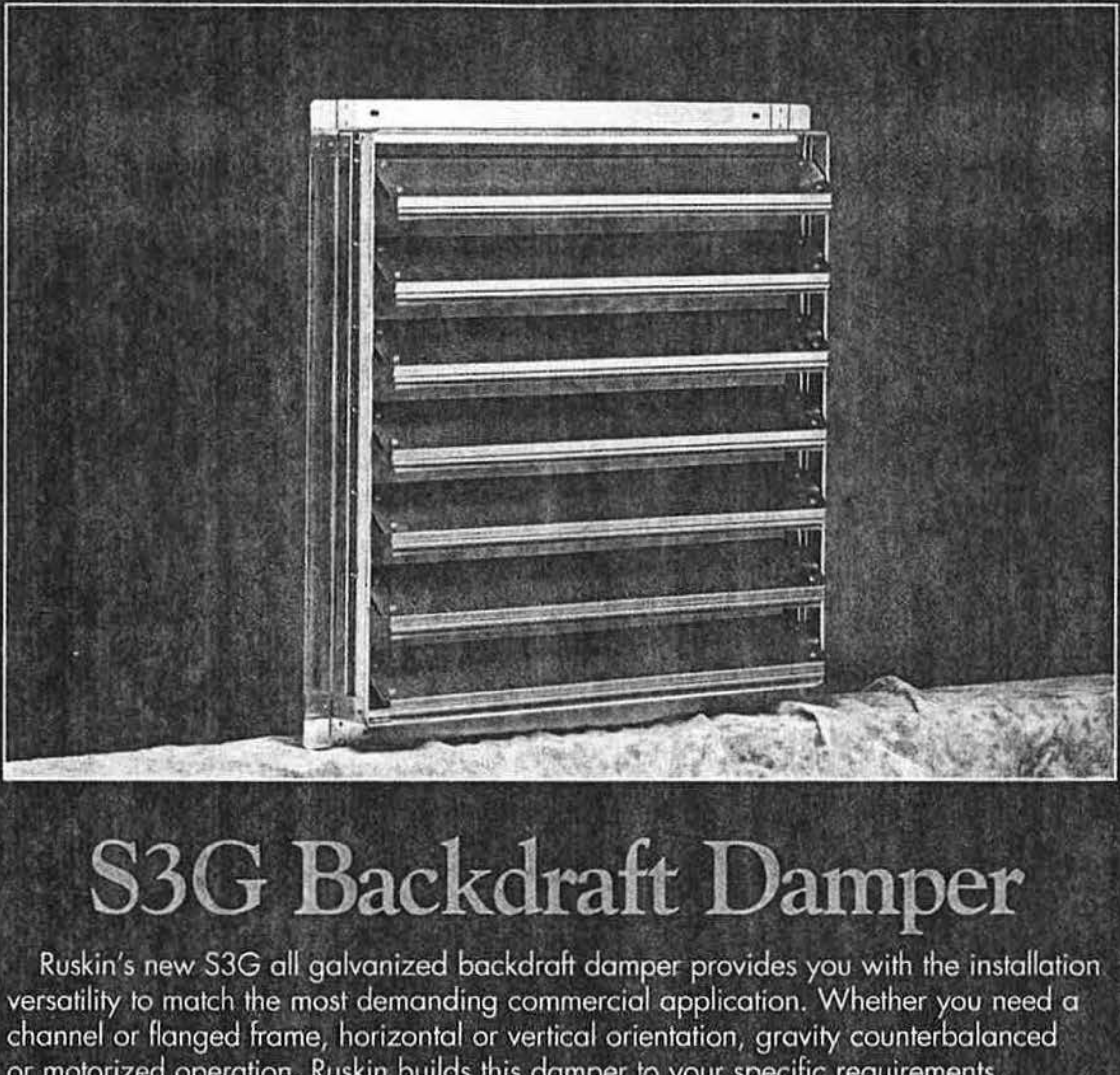

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cost of the improvements was approximately \$220,000.

Comparing Buildings

In our analysis, the annual energy use index (EUI) for the base case building dropped from 71 kBtu/ft^2 (224 kWh/m^2) to only 27 kBtu/ft^2 (85 kWh/m^2) for the optimized building. In Florida, the average energy use of 160 state-owned office buildings in Florida in 1991 was 67 kBtu/ft^2 (211 kWh/m^2). FSEC's previous facilities in Cape Canaveral used about 79 kBtu/ft^2 (249 kWh/m^2).

Control and Metering

The new facility has an extensive energy management system (EMS) capable of optimizing and verifying system performance. Recent studies have emphasized the importance of building energy monitoring to properly commission HVAC systems in order to realize their maximum efficiency potential [17]. This will enhance our ability to proffer lessons learned to the Florida design community through our Building Design Assistance Center.

Conclusions

An analysis of the new FSEC building indicates that large benefits in reducing energy consumption in a hot-humid climate can be obtained from improvements to the building and its equipment. A 62% overall (71 - 27 kBtu/ft^2 yr) reduction in energy use over code-mandated levels was predicted by simulation analysis. The most important measures included a high-efficiency lighting system with daylighting, spectrally-selective windows and a high-efficiency HVAC system engineered for effective humidity removal.

Other identified measures included reducing the solar absorptance of the roof, lowering the ventilation rate from 20 to 15 cfm (7.1 L/s) per person using demand controlled ventilation and *Energy Star* personal computers.

Acknowledgments

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